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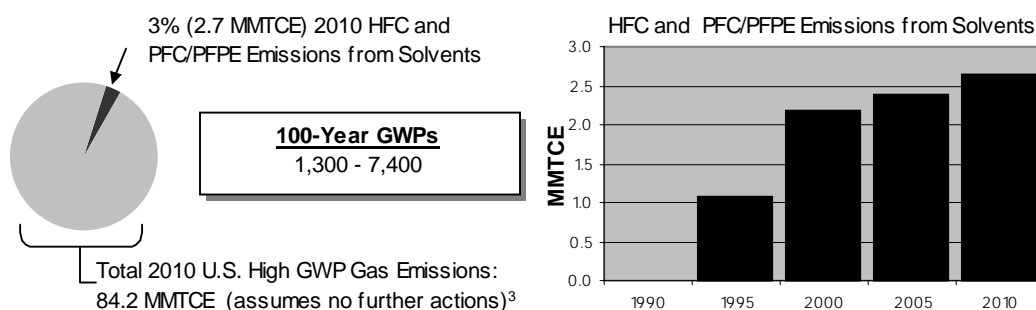
8. Cost and Emission Reduction Analysis of HFC and PFC/PFPE Emissions from Solvents in the United States

8.1 Introduction

Historically, CFC-113, carbon tetrachloride, and methyl chloroform have been used as solvents in the United States for a wide range of cleaning applications including precision, electronics, and metal cleaning (UNEP, 1999) (see Appendix 8.1). The solvent industry has phased out most of its ozone-depleting substance (ODS) use and continues to research alternative cleaning practices and replacement solvents. These alternatives generally offer economic, health, and environmental benefits.

The vast majority of the market, primarily the metal and electronics cleaning end-uses, no longer uses high ozone depleting potential (ODP), high GWP compounds like CFC-113, methyl-chloroform, perfluorocarbons (PFCs), and perfluoropolyethers (PFPEs). Instead, they use alternative technologies such as no-clean, aqueous and semi-aqueous cleaning; and solvents such as hydrofluorocarbons (HFCs), hydrofluoroethers (HFEs), hydrocarbons, and alcohols.¹ Although climate impact is still a concern using some of these substances, these replacement technologies are considered advantageous. Certain solvent applications, however—particularly precision cleaning end uses—require the use of hydrochlorofluorocarbons (HCFCs) such as HCFC-141b and HCFC-225 ca/cb (prior to the HCFC phaseout), and to a lesser extent PFC/PFPEs as replacements because these solvents have high reliability, excellent compatibility, good stability, low toxicity, and selective solvency.² Projected HFC and PFC/PFPE emissions from precision cleaning end uses dominate the greenhouse gas impact from the solvents sector (see Exhibit 8.1).³

Exhibit 8.1: U.S. Historical and Baseline HFC and PFC/PFPE Emissions from Solvents



¹ HFC-4310mee is the most common HFC used in solvent cleaning in the United States. This report makes use of the broader term HFC to refer to several alternatives used in different industries, including HFC-4310mee, HFC-365mfe, a cyclic HFC, and HFC-245fa.

² PFC/PFPEs is a term used to describe a diverse collection of perfluorocarbons (PFCs) and perfluoropolyethers (PFPEs) employed for solvent applications.

³ An explanation of the business-as-usual scenario under which baseline emissions are estimated appears in the Introduction to the Report.

The relatively low boiling points (50-90°C) of HFCs and PFC/PFPEs contribute to their rapid volatilization; the resulting greenhouse gases have 100-year GWPs ranging from 1,300 to 7,400⁴ times the warming potential of carbon dioxide. In the absence of further reduction efforts, under a business-as-usual scenario, the U.S. is projected to emit 2.65 MMTCE of HFCs and PFC/PFPEs by 2010 from solvent applications.

8.2 Historical and Baseline HFC and PFC/PFPE Emission Estimates

Historic emissions from precision cleaning solvents were estimated to be 2.1 MMTCE in 1999 as presented in Exhibit 8.2. This estimate was made using EPA's Vintaging Model, discussed in detail in Appendix A. Although EPA's model is a comprehensive approach, uncertainties still exist with regard to the levels of equipment sales, equipment characteristics, and end-use emission profiles that were used to estimate annual emissions for various compounds. Projections for the years 2000, 2005, and 2010 were calculated using the same model, assuming 100 percent market penetration of alternative solvents by 2015 (see Exhibit 8.3).⁵ There are several regulatory programs (e.g., Significant New Alternatives Policy Program determines the acceptability of substitutes to ODS) in place to limit use of ODS substitutes in some applications. These actions are expected to result in significant reductions in ODS substitute emissions. These reductions are incorporated in the baseline estimate of emissions. The cost analysis presented here evaluates the cost of reducing emissions from this baseline.

Exhibit 8.2: Historical U.S. HFC and PFC/PFPEs Emissions from the Solvent Sector (1990-1999)										
	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Emissions (MMTCE)	0.0	0.0	0.0	0.0	0.2	1.1	2.0	2.0	2.1	2.1

Source: EPA, 2000 (for 1990-1998) and EPA estimates (for 1999).
Notes:
Emissions are not broken down by chemical to avoid disclosure of confidential business information.
Conversion to MMTCE is based on the GWPs listed in the Introduction to the report.

Exhibit 8.3: Baseline U.S. HFC and PFC/PFPEs Emissions from the Solvent Sector (2000-2010)			
	2000	2005	2010
Emissions (MMTCE)	2.2	2.4	2.7

Notes:
Forecast emissions are based on a business-as-usual scenario, assuming no further action.
Emissions are not broken down by chemical to avoid disclosure of confidential business information.
Conversion to MMTCE is based on the GWPs listed in the Introduction to the report.

⁴ 7,400 is used in this report as the GWP for PFC/PFPEs; it is derived from the respective GWPs of the compounds in this group.

⁵ Given that emissions of ODS substitutes occur from thousands of different kinds of equipment and from millions of point and mobile sources throughout the United States, emission estimates are made using analytical tools such as the EPA Vintaging Model.

8.3 HFC and PFC/PFPE Emission Reduction Opportunities

HFC and PFC/PFPE emissions from the solvents sector can be eliminated or mitigated through several technologies and practices as presented in Exhibit 8.4. The emissions and uses of these compounds can be further reduced by retrofitting equipment and improving containment of the solvents, initiating recycle and reuse programs, and introducing carbon adsorption technologies. Ongoing research continues to identify low GWP alternatives that could replace high GWP PFCs and HFCs. Certain HFCs and PFC/PFPEs are currently essential to carrier fluid and precision cleaning applications where compatibility of the alternatives is an issue. Four approaches for solvent emission reduction are summarized below (March Consulting Group, 1998 and 1999; UNEP, 1999):

- improved solvent system designs;
- recycle and recovery;
- alternative cleaning technologies; and
- alternative cleaning solvent fluids.

Improved Equipment and Cleaning Processes Using Existing Solvents

Engineering controls, improved containment, and other abatement technologies represent methods for reducing emissions of PFCs and HFCs while new chemicals and technologies are being evaluated. Improved engineering controls include increasing freeboard height, installing freeboard chillers, and using automatic hoists (UNEP, 1999; ICF Consulting, 1992). Likewise, for some applications where adaptations of other types of cleaning processes are not feasible, there are significant opportunities to reduce emissions of solvents during the cleaning process. By improving the design of the solvent bath enclosure and of vapor recovery condensing systems, for example, it is possible to minimize evaporative losses (March Consulting Group, 1998 and 1999). Work is also underway to develop processes that do not require solvents with ODPs or high GWPs.

Exhibit 8.4: Overview of Solvent Technologies Used Worldwide

	Applicability to End-Use		
	Metal	Electronics	Precision
Solvent Classes			
Chlorinated Solvents	✓	✓	✓
HCFC Solvents (HCFC-225 ca/cb and HCFC-141b)		✓	✓
HFC-4310mee	✓	✓	✓
PFC/PFPE Solvents			✓
HFE Solvents	✓	✓	✓
Hydrocarbons	✓	✓	✓
Alcohol solvents	✓	✓	✓
Brominated Solvents	✓	✓	✓
Methyl Siloxanes	✓	✓	✓
Alternative Cleaning Technologies			
Aqueous Cleaning	✓	✓	✓
Semi-Aqueous Cleaning	✓	✓	✓
No-Clean Processes	✓	✓	
▪ Low-solids flux or paste			
▪ Inert Gas Soldering			

HFC and HFE prices are much higher than those of CFC-113 and HCFC-141b, which results in significant improvements in the containment technology of degreasers, defluxers, and dryers. Some cleaning equipment using HFC solvents are being retrofitted with higher freeboard and low-temperature secondary cooling coils. Also, in some cases, other improvements have been made to reduce drag-out losses of solvent from these systems to a very low level. In cases where certain HFCs and PFC/PFPEs are essential solvents in precision cleaning end uses, it is possible to reduce emissions to a minimum level by implementing good handling practices (UNEP, 1999).

Recycle and Recovery

In instances where HFCs and PFC/PFPEs continue to be used for performance reasons, the emissions can be minimized by implementing recycle and reuse programs (UNEP, 1999). Used solvent may be recovered through a distillation process that can take place in either the degreasing unit or the solvent still (Clement *et al.*).

Solvent recovered from electronics applications cannot be recycled indefinitely because reclaimed solvent would not have the same composition as the virgin material, and hence cleaning properties would be altered or diminished. In metal cleaning applications, solvent wastes can be recycled, and the resulting waste used in fuel blending programs. Recycled solvents are rarely used in precision cleaning due to perceived impurities. On-site solvent recovery could be utilized and such programs can be cost-effective. Even companies that purchase small, inexpensive solvent reclamation equipment offset the costs of solvent disposal (UNEP, 1999).

Alternative Solvent Technologies

In addition to the emission reduction approaches that use improved equipment and cleaning practices, there are several not-in-kind (NIK) technology processes and solvent replacements that can be used to substitute for PFC and HFC-containing systems. Approaches that use aqueous and semi-aqueous processes are described in detail in Appendix 8.1.

Alternative Solvent Fluids

In electronics, metal, and some precision cleaning end uses, alternative organic solvents with lower GWPs are being manufactured and integrated into the industry. Some of these solvents, such as HFCs, HFEs, hydrocarbons, alcohols, volatile methyl siloxanes, brominated solvents, and non-ODS chlorinated solvents, can be used as alternatives to PFC/PFPEs, CFCs, and HCFCs. This solvent substitution can have a major impact on reducing emissions of high-GWP gases. HFC, PFC/PFPE, and HCFC use is very small in the metal and electronic cleaning end uses, and generally occurs only in cases where there are no possible alternatives. These solvents are primarily used for precision cleaning and carrier fluid applications as alternatives to CFC-113 and methyl chloroform (as described in Appendix 8.1).

8.4 Cost Analysis

Cost analyses were conducted for the following mitigation options: alternative solvents, NIK alternatives, and retrofit options. The most viable mitigation option to reduce emissions from the solvents sector is to adopt alternative solvents. All cost analyses were performed for four- and eight-percent discount rates, with a ten-year project lifetime. Financial assumptions and results specific to each emission reduction option are presented below. Exhibit 8.5 summarizes HFC and PFC/PFPE emission reductions by cost per metric ton of carbon equivalent (TCE).

Alternative Solvents

Adopting an alternative solvent is an approach that can be used to reduce the GWP-weighted emissions from the solvents sector. This option can be relatively inexpensive on a carbon basis given similar chemical prices and use rates for the available HFC and HFE solvents (Kenyon, 2000). For the purposes of this report, it was estimated that a significant portion of the PFC solvent market could be replaced by alternative solvents—25 to 50 percent—while five to 20 percent of the HFC solvent market could be replaced. Based on expert opinion, chemical prices are higher using alternative solvents, with increased costs ranging from \$0.20 to \$1.65 per kilogram of HFE or HFC. Of the available options, alternative solvents can have the largest impact on 2010 baseline emissions at the lowest cost (\$0.88/TCE). They represent a potential reduction of 0.8 MMTCE, over 30 percent of the baseline forecast.

NIK Replacements

Aqueous and semi-aqueous NIK replacement options can displace HFC, PFC, and HCFC usage in some solvent applications. For the purposes of this report, it was estimated that up to 10 percent of the HFC solvent use could be replaced with both aqueous and semi-aqueous NIK alternatives. For the cost analysis, it is assumed that the incremental investment required to convert a typical process may cost up to \$60,000 with annual operating savings between \$1,000 and \$2,000. Annual emissions avoided for a standard unit range from 300 to 1,000 kilograms/year (ICF Consulting, 1992). Together, NIK alternatives have the potential to reduce emissions from the solvents sector by about 3 percent of the 2010 baseline.

Retrofit Options

The costs of retrofitting solvent processes to reduce emissions could range from \$2,000 to over \$100,000. Given that solvent prices are relatively high, the analysis assumed that most solvent users will opt to invest in equipment options to minimize solvent losses in the baseline. In many cases, investments in retrofit options will be profitable for the end users. It was estimated that up to 10 percent of the HFC solvent market could be affected by implementation of emission reduction retrofit technology. For the cost analysis it was assumed that a \$20,000 investment might reduce annual emissions from a typical solvent process by up to 10 percent, for an annual reduction of 40 kilograms (Durkee, 1997). Retrofit options could reduce emissions at relatively low costs (\$42.45 and \$71.24 per TCE at four and eight percent discount rates, respectively) by 0.04 MMTCE in 2010, or two percent of baseline emissions.

Exhibit 8.5: Emission Reductions and Cost in 2010

Option	Break-even Cost (\$/TCE)		Incremental Reductions		Sum of Reductions	
	Discount Rate		MMTCE	Percent	MMTCE	Percent
	4%	8%				
Alternative Solvents	0.88	0.88	0.82	31%	0.82	31%
NIK Semi-Aqueous	9.63	11.55	0.03	1%	0.85	32%
NIK Aqueous	21.57	25.02	0.04	2%	0.89	34%
Retrofit Options	42.45	71.24	0.04	2%	0.93	35%

Notes:

2010 baseline emissions from the solvents sector equal 2.7 MMTCE.

Conversions to MMTCE are based on the GWPs listed in the Introduction to the report.

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Appendix 8.1: Solvents End Uses, Alternatives, and Technologies

End Uses and Cleaning Equipment

Electronics Cleaning

Electronics cleaning primarily involves the removal of resin flux from printed circuit boards (PCB) after soldering has been completed. Flux is a product that is applied to a PCB to enhance the quality of the solder joint by reducing the concentration of oxygen present at the time of soldering. While much of the flux is comprised of alcohols (volatilized during the soldering operation), many of the solids contained in the flux formulation remain on the PCB after soldering. CFC-113 and, to a lesser extent, methyl chloroform have traditionally been used as solvents in electronics cleaning to remove solids left behind after flux is incompletely volatilized. If not removed, these solids may cause performance-related problems and are visually unacceptable.

Precision Cleaning

Precision cleaning may apply to either electronic components or metal surfaces, but in either case is characterized by applications that require a high level of cleanliness in order to ensure satisfactory performance of the product being cleaned. Examples of products that might require precision cleaning include computer disk drives and navigational instruments. Both CFC-113 and methyl chloroform have been used to a similar extent in precision cleaning applications, CFC-113 because of its chemical stability and zero flammability, and methyl chloroform because of its high solvency and rapid evaporation rate.

Metal Cleaning

Metal cleaning is a process that removes a wide variety of contaminants from metal surfaces during manufacturing or maintenance services. At each stage in the manufacturing process, for example, contaminants must be removed from the piece to ensure a clean metal surface for the next step in the production process. The metal contaminants most often removed are greases and oils (used primarily as lubricants in the cutting and forming of metal pieces), particulate matter, and inorganic soils. In addition to primary metal and production cleaning, other metal changing operation uses for solvents include periodic maintenance of plant and equipment, and repair and service of equipment (UNEP, 1999). Most metal cleaning operations have used methyl chloroform because of its relatively low toxicity, high solvency power, low surface tension, and relatively low boiling point.

Solvent Cleaning Equipment

The three types of equipment typically used in solvent cleaning applications are cold cleaners, open top vapor degreasers, and conveyORIZED vapor degreasers.

Cold cleaners. These are most often tanks in which a contaminated piece is dipped into the cold solvent to remove particulate matter. These cleaners are fairly low in both capital and operating costs, because they have no heating units and require little if any energy consumption.

Open top vapor degreasers. These are the most widely used types of solvent cleaning equipment in the United States. They operate by heating the solvent in the bottom of the unit so that a vapor zone is created. The piece to be cleaned is lowered into the vapor zone and the solvent vapor acts to clean the contaminants from the piece. As the piece is raised out of the cleaner, the solvent is condensed back into a liquid and returns to the bottom of the unit.

Conveyorized vapor degreasers. These operate on the same principle as the open top units. However, they are designed for continuous operation and pieces to be cleaned are carried through the unit on a conveyor. This design allows for a greater throughput per cleaning machine and reduces the need for human interactions in the cleaning process.

Overview of Solvents and Cleaning Technologies

Solvents

HFCs and PFC/PFPEs are the primary high-GWP gases that are emitted from solvent use. Currently, the most popular alternative solvents are chlorinated solvents, HFEs, hydrocarbons, alcohol solvents, methyl siloxanes, and brominated solvents. HCFCs, HFCs, and PFCs are described in this analysis because of their continued use in various precision cleaning end uses.

Chlorinated Solvents. Chlorinated solvents are feasible alternatives to HFCs in precision cleaning. The process is similar to traditional solvent cleaning processes, with the exception of the solvent used. Non-ODS chlorinated solvents such as perchloroethylene, trichloroethylene, and methylene chloride can be used in traditional vapor degreasing equipment with additional engineering controls to limit emissions or in newly designed “tight” equipment that keeps emissions to a minimum.

HCFC Solvents. HCFCs are serving some limited and unique applications where other suitable alternatives have not been identified, including: cleaning delicate materials (such as cultural heritage and archival property); cleaning assemblies or components with sensitive materials or particular soils; cleaning certain oxygen systems; cleaning where explosive or flammable conditions are possible; and serving as a carrier of oil in precision cleaning applications. HCFCs are used in precision and electronic cleaning where compatibility of the solvent with the substrate to be cleaned is critical. The currently used HCFC in this application is HCFC-225ca/cb. All HCFCs, including HCFC-225, are subject to additional reductions in production and consumption with a phaseout in the United States by 2014.

HFC Solvents. In the mid-1990s, HFC-4310mee was introduced to replace CFC-113 in many applications. It has better solvent properties than PFCs and has more desirable environmental properties, such as zero ozone depletion potential and a very short atmospheric lifetime compared to PFCs and CFC-113. HFC-4310mee, both used alone and with additives such as alcohol, hydrochlorocarbons, and hydrocarbons in azeotropic proportions, was introduced to meet critical cleaning needs to replace CFC-113 in electronics defluxing, ionic impurities removal, and precision cleaning applications. HFC-4310mee has also replaced some uses of PFC and CFC-113 as a carrier fluid for lubricants applied to computer hard disks, in some precision bearing lubrication applications, for displacement drying of minute electronic and optical components, and as a flush fluid for removal of particulates in precision cleaning. The Police Scientific Development Branch of Scotland Yard has tested and qualified HFC-4310mee as an acceptable solvent alternative to CFC-113 for use in developing latent fingerprints from porous material, such as paper. Likewise, federal and some state forensic laboratories in the United States and authorities in Japan have also qualified HFC-4310mee for these uses and continue to make inroads into forensic uses of CFC solvents that are currently allowed under terms of the global laboratory and analytical essential use exemption. HFC-4310mee has also replaced CFC-113 as an essential part of a rain repellent formulation for aircraft windshields. Although HFC solvents are used in many applications, the total global use in solvents and coatings is very small and estimated to be less than 1,000 to 2,000 metric tons, which was less than one percent of global CFC-113 uses in 1989 (UNEP, 1999).

Perfluorocarbon Solvents. Perfluorocarbons (PFCs) such as C_5F_{12} , C_6F_{14} , C_7F_{16} , and C_8F_{18} , were introduced as substitutes for ODS in the early 1990s, and are also used in some applications in which ODS solvents were never used. Though they have been replaced by other substances (predominantly

HFEs) in many of the processes for which they have historically been used, PFCs were (and are still, to some degree) used as a carrier fluid for fluorolubricants in computer hard disk drives, as a flush fluid for particulate removal in precision cleaning, as a coolant in other electronic components, and as a rinsing agent in a co-solvent process for cleaning printed circuit boards and mechanical components containing oil, grease, and other soils. PFCs are being replaced in many applications by lower GWP HFEs and HFC-4310mee (UNEP, 1999).

HFE Solvents. Methyl perfluorobutyl ether is a mild solvent that can be blended with alcohols and other substances to increase solvency. It is a high cost solvent that is used for defluxing and/or degreasing high value parts and printed wiring assemblies (UNEP, 1999; March Consulting Group, 1998 and 1999). A family of fluorinated ethers (HFEs) was also developed during the mid-1990s as replacements for chlorinated and/or fluorinated solvents. Specifically, HFEs have successfully replaced PFCs, CFC-113, 1,1,1-trichloroethane, and HCFCs in certain precision cleaning operations, as well as in industrial aerosol solvent formulations. These HFEs and the various azeotropic formulations based on HFEs are the newest substitutes and are used in critical cleaning applications where compatibility with the substrate to be cleaned is essential. HFEs are also being utilized as replacements for some of the HCFC-141b and HCFC-225ca/cb solvent uses scheduled for phaseout. The advantages of HFEs are that they have no ozone depleting potential, have low toxicity, and are non-flammable. The GWPs of commercially available HFE-7100 and HFE-7200 are 390 and 55, respectively. HFC-4310mee has a GWP of 1,300, a factor of 4 to 30 times higher than these HFEs. However, HFEs will not always be substitutes for HFC-4310mee due to application specific requirements.

Hydrocarbon and Alcohol Solvents. Hydrocarbons are primarily used for metal and general cleaning requiring good solvency. Alcohols (i.e., isopropyl alcohol) and hydrocarbons are used for electronics and precision cleaning (UNEP, 1999; March Consulting Group, 1998 and 1999). Hydrocarbons vary in level of toxicity, and those with cyclic or aromatic molecular structure have a higher level of toxicity. The disadvantages of hydrocarbons and isopropyl alcohol include flammability risks and minor health hazards to handlers of these solvents (UNEP, 1999).

Volatile Methyl Siloxanes. The volatile methyl siloxanes are used as mild solvents suited primarily for cleaning silicone and other light, nonpolar residues. Since this is a high cost solvent, it is used for defluxing and/or degreasing high value parts and printed wiring assemblies. These solvents are also flammable and have low flash points. Therefore, these compounds are used in specialized equipment (UNEP, 1999).

Brominated Solvents. Some international manufacturers and suppliers are marketing two brominated solvents -- n-propyl bromide (nPB) and chlorobromomethane (CBM)—as replacements for HFC-4310mee, CFC-113, and the HCFCs (HCFC-141b and HCFC-225ca/cb). Both CBM and nPB are short-lived in the atmosphere and have small, positive, though uncertain, ODPs.

- **N-propyl bromide** is an aggressive solvent with a moderate boiling point that generally requires a stabilizer package and does not have a flash point (UNEP, 1999). This solvent has a low ODP and a low GWP. However, because nPB has a very short atmospheric lifetime of only 11 days, the ODP will depend on where it is emitted and the time of the year. It is compatible with metals, has a low tendency to cause corrosion, and can be used in most vapor degreasing equipment. The economic benefits of nPB are that it is easily recycled and moderately priced. The EPA, under the SNAP program, has not yet approved nPB as a substitute for ODS pending the availability of further ODP and toxicity data. However, its use in the rest of the world is rapidly increasing.
- **CBM** has unacceptably high toxicity, and the EPA has disapproved its use as a solvent in the U.S. under SNAP (UNEP, 1999).

Cleaning Technologies

CFC-113 and PFCs can be replaced in many applications with NIK alternatives by either modifying the process or cleaning requirements without compromising safety, performance, or compatibility. These NIK technologies are: (1) water-based cleaning and (2) no-clean processes, described below (UNEP, 1999).

Water-Based Cleaning. Water-based cleaning involves aqueous and semi-aqueous methods that have already been adopted widely in the metal and electronics cleaning sectors to replace CFC-113 and methyl chloroform. They can also be applied to many applications of HCFC-141b.

- **Aqueous cleaning** is a promising alternative process. The process uses a water-based cleaning solution that often contains a detergent to remove contaminants. The products are then rinsed with water. Aqueous processes have lower material costs than traditional solvent processes due to the low cost of water, but energy costs are comparable to and in some instances higher than CFC-113 and methyl chloroform processes. Depending on the level of contamination and local discharge regulations, wastewater treatment may be required before the water is discharged. However, in order to minimize wastewater discharge and the cost associated with wastewater discharge processes, “closed-loop” systems are available in which the water is separated out of the cleaning solution, treated, and reused (ICF Consulting, 1992).
- **Semi-aqueous cleaning**, or hydrocarbon-surfactant cleaning, is another alternative process that is likely to be widely used as a replacement in electronics, metal, and precision cleaning. A semi-aqueous process uses a cleaning solution, often a hydrocarbon/surfactant combination, to remove contaminants such as metal particulates, oil, and grease. The products are then rinsed with water. Semi-aqueous processes have lower material and energy costs than traditional solvent processes that use CFC-113 and methyl chloroform. Depending on the level of contamination and local discharge regulations, wastewater treatment may be required before the rinse water is released. As with aqueous cleaning, “closed loop” systems can be purchased that allow the re-use of water used in the cleaning process (ICF Consulting, 1992). Some of the benefits of using a semi-aqueous process are good cleaning ability, suppressed vapor pressure, non-alkalinity, reduced evaporative loss, potential decrease in solvent consumption, and ability of some formulas to separate easily from water. Some of the disadvantages of this process can include: flammability concerns that might require improved equipment design; many solvents used in the system are VOCs; and some applications may require high purity water, which is expensive (UNEP, 1999).

No-Clean Processes. No-clean processes refer to technologies that many manufacturers, especially in the electronics sector, have been able to implement without the need for traditional cleaning (March Consulting Group, 1998 and 1999). For example, “no-clean” soldering processes result in the elimination of cleaning and thus the need to use any solvent. There are two kinds of processes that could be implemented to switch a manufacturing line to a “no-clean” process, which are described below.

- **Use of low-solids flux or paste.** Low-solids fluxes serve the same purpose as their traditional counterparts, but leave significantly less residue on the PCB after soldering. They often contain two to five percent solids, as compared to 10 to 40 percent solids found in traditional fluxes. Many companies have tested low-solid fluxes in their production facilities and have determined that the small amount of residual flux remaining from the use of these formulations does not damage the quality of the board.
- **Soldering in a controlled atmosphere.** Controlled atmosphere soldering is identical to traditional wave and reflux soldering operations. The only difference is that the atmosphere is inerted by pumping nitrogen into the soldering chamber to remove oxygen and allow for a more efficient operation. Soldering in an inert atmosphere results in a significant reduction in the amount of flux and solder paste used due to the high efficiency of the process (ICF Consulting, 1992).